DASA 1853

DASA-AEC-LOVELACE FOUNDATION BLAST-SIMULATION FACILITY

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Donald R. Richmond, Charles S. Gaylord,
Edward G. Damon and R. V. Taborelli

Technical Progress Report
on
Contract No. DA-49-146-XZ-372

This work, an aspect of investigations dealing with the Biological Effects of Blast from Bombs, was supported by the Defense Atomic Support Agency of the Department of Defense.

Lovelace Foundation for Medical Education and Research
Albuquerque, New Mexico

August 1966

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FOREWORD

This report describes the DASA-AEC-Lovelace Foundation Blast-Simulation Facility which is located on Sandia Base, New Mexico. The facility has been developed over the past eleven years. The effort was first supported by the Civil Effects Branch of the Division of Biology and Medicine, U. S. Atomic Energy Commission, Contract No. AT (29-1) 1242, to supplement blast-biology studies in personnel shelters on full-scale nuclear tests. Since 1959-60, the program has been supported by the Medical Division of the Defense Atomic Support Agency, Department of Defense, under Contracts No. DA-49-146-XZ-055 and DA-49-146-XZ-372 for the purpose of studying the Biomedical Effects of Blast and Shock.

ABSTRACT

The DASA-AEC-Lovelace Foundation Blast-Simulation Facility for the biomedical investigation of the effects of Blast and Shock is described in detail.

Photographs, descriptions, and specifications of four air-driven shock tubes, ranging from 12 to 72 in. in diameter, and a concrete-pad, high-explosive test site are given. The instrumentation system and shock-tube and gauge-calibration procedures are included.

Test parameters for each shock tube are briefly summarized and supported by typical pressure-time patterns and calibration curves.

ACKNOWLEDGMENTS

The authors wish to acknowledge their indebtedness for a number of contributions over the years that were of significance in developing the DASA-AEC-Lovelace Blast Tube Facility; namely, to Dr. Clayton S. White who appreciated the need for a specialized blast-simulation capability during the 1953 Nevada Nuclear Test Series, and who has guided the development of the facility since its inception in 1955; to Mr. James Clark who designed the initial 12-24-42-in. shock tube, and in 1954-55, supervised its assembly and installation; to Sandia Corporation for supplying much of the early instrumentation; to Mr. Edward E. Fletcher who initially looked after all electronic components and, with the subsequent help of Mr. John A. Price, continued to lend support in this regard; and to Mr. Glen L. Paxton who in recent times has taken care of instrument installation and maintenance.

Also, appreciation is expressed to the following individuals for critical aid and understanding; to Dr. Charles L. Dunham, Mr. Robert L. Corsbie and Mr. L. Joe Deal, all of the Division of Biology and Medicine, U. S. Atomic Energy Commission, who helped arrange funding support up to 1960; to Captain John A. O'Donoghue (MC) USN, Colonel Robert H. Holmes (MC) USA and Colonel Gerrit L. Hekhuis (MC) USAF who, during their assignment as The Surgeon, Defense Atomic Support Agency, Department of Defense, appreciated the continued need for developing the shock-tube facility and helped obtain uninterrupted fiscal support since 1959.

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INTRODUCTION

The primary purpose of this facility is to generate air blasts for biomedical investigation of the effects of blast and shock. The biological effects from blast in shock tubes have been found to be similar to those produced by high explosives or nuclear devices, with shock tubes having several advantages over high explosives for physiological investigation and compilation of dose-response curves: (1) long-duration shock waves are economically obtained and certain waveforms easily simulated and repeated in shock tubes — an essential requirement of biological tests which involve large serial samples of statistical nature; (2) instruments to record physiological process, pressures inside the animal, and specialized optical and X-ray systems can be located close to the shock tube and the shape of the waveform are readily varied and tailored by changing the configuration of the shock tube; and (4) test procedures and results are not affected by adverse weather conditions.

In order to investigate blast effects under controlled conditions, air-driven shock tubes varying from one to six feet in diameter were designed, constructed, and operated by Lovelace Foundation personnel. To generate the wide variety of pressure-time patterns essential to biological studies, nearly a hundred different shock-tube configurations have been utilized, with more than half of these tested using biological specimens. The tolerance of 12 animal species, ranging in size from mice to cattle, has been determined with interspecies correlations extrapolated to help assess blast hazards in man.

DESCRIPTION AND SPECIFICATIONS

This facility consists of four highly versatile shock tubes and a concrete-pad, high-explosive site.

42-72-Inch Diamater Shock Tube

This tube (Figures 1 and 2) has an overall length of 179 ft. The 15-ft compression chamber is 42 in. in diameter as is the first 125 ft of the expansion chamber after which this diameter increases to 72 in. over a 9-ft conical section. The 72-in. diameter test section is 30 ft long and is closed with a blind flange. The 9-ft conical section is equipped with vent ports to introduce rarefaction of the waveform. The entire shock tube is mounted on a system of wheels and rails for ease of component interchange.

24-40-Inch Diameter Shock Tube

The overall length of this shock tube (Figure 3) is 70 ft. The compression chamber is 17 ft 5 in. long with a diameter of 40.5 inches. From the

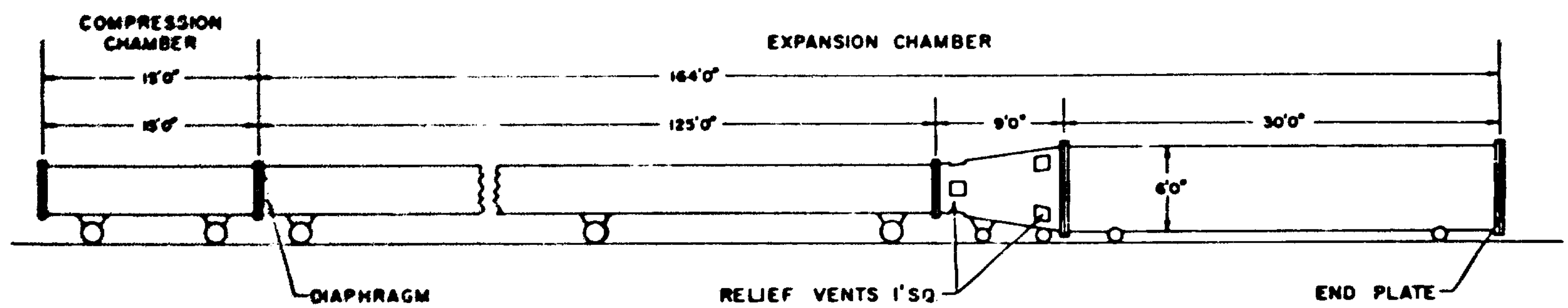


Figure 1. Detail Diagram 42-72-Inch Diameter Shock Tube.

Figure 2. 42-72-Inch Diameter Shock Tube.

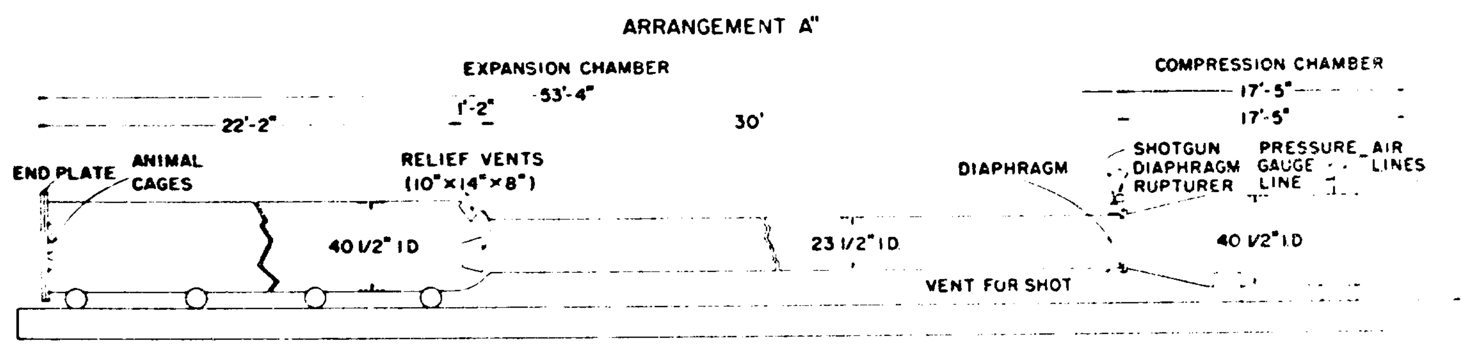


Figure 3. Detail Diagram 24-40-Inch Diameter Shock Tube (Arrangement A").

diaphragm station, the first 30 ft of the driven section has a diameter of 23.5 in. and increases to 40.5 in. over a 3-ft, bell-shaped section that connects to a 22-ft test section. Since this tube is normally operated closed, relief vents in the bell-shaped section serve to tailor the waveform. This tube has recently been modified to provide for pressurization and evacuation of the expansion section to simulate reduced and increased ambient pressures (Figures 4 and 5). For these tests, the 17-ft 5-in. x 40-in. driver was replaced with a 3-ft section 24 in. in diameter to reduce the volume of gas entering the expansion section upon firing. A storage-tank reservoir connected to the driven section, either pressurized or evacuated, is used to hold the desired pre-shot pressure level in the expansion chamber by increasing or dumping pressure as required.

24-Inch Diameter Shock Tube

A recent modification of this tube (Figure 6) has increased its length from 80 to 143 ft. The tube is circular and of uniform cross-sectional area for the first 97 ft at which point the underside of the tube becomes flat for a distance of 32 ft. The remaining 14 ft resumes the circular configuration of the forward section. A 17-ft test section, located 35 ft downstream, contains five 8 x 8 x 2-1/2-in. recesses for holding small animal specimens. The depth of these recesses may be increased by adding extensions and the geometry changed by using blocks of varied shapes. The 32-ft, flat-bottomed test section of the expansion chamber is equipped with five access plates 17 x 17 in. square to allow for the insertion of different test geometries into the tube. The compression chamber is variable and was increased to 10 ft for the present configuration.

12-Inch Diameter Shock Tube

For its entire length, this shock tube is uniformly circular in cross section (Figures 7 and 8). It has a 2.5 ft long compression chamber. When employed open-ended, the expansion chamber is 30 ft long; when operated closed, the length is 17 ft. The expansion chamber of this tube can be pressurized or evacuated to test blast response of small animals at increased or reduced ambient pressures. This tube is equipped with gauge mounts for dynamically calibrating gauges by either the gauge-pairing or shock-velocity methods.

Diaphragms

For the 12-, 24-, and 24-40-in. diameter shock tubes, diaphragms consist of one or more sheets of Du Pont Mylar® (polyester film) pre-drilled to match the flange bolts of the tubes. The inner edge of the tube at the first flange downstream of the diaphragm is rounded smooth to prevent cutting the diaphragm as it expands under pressure.

Diaphragms for the 42-72-in. diameter shock tube (Figure 9) also consist of multiple sheets of Mylar, up to 20 in number, or one or more sheets of aluminum, up to a total thickness of 1/4 inch. Diaphragms are clamped onto the flange of the driver section which is equipped with a raised "S"-shaped edge that locks into a matching contour on the driven section. This arrangement provides an air-tight seal when the two sections are bolted together.

Diaphragm rupture in the 24-, 24-40-, and 42-72-in. diameter shock tubes is normally initiated by a 12-gauge shotgun mounted on the tube so it fires downward through the diaphragm and a hole in the bottom of the tube. Diaphragms of the 12-in. diameter tube and of the 24-40-in. diameter tube,

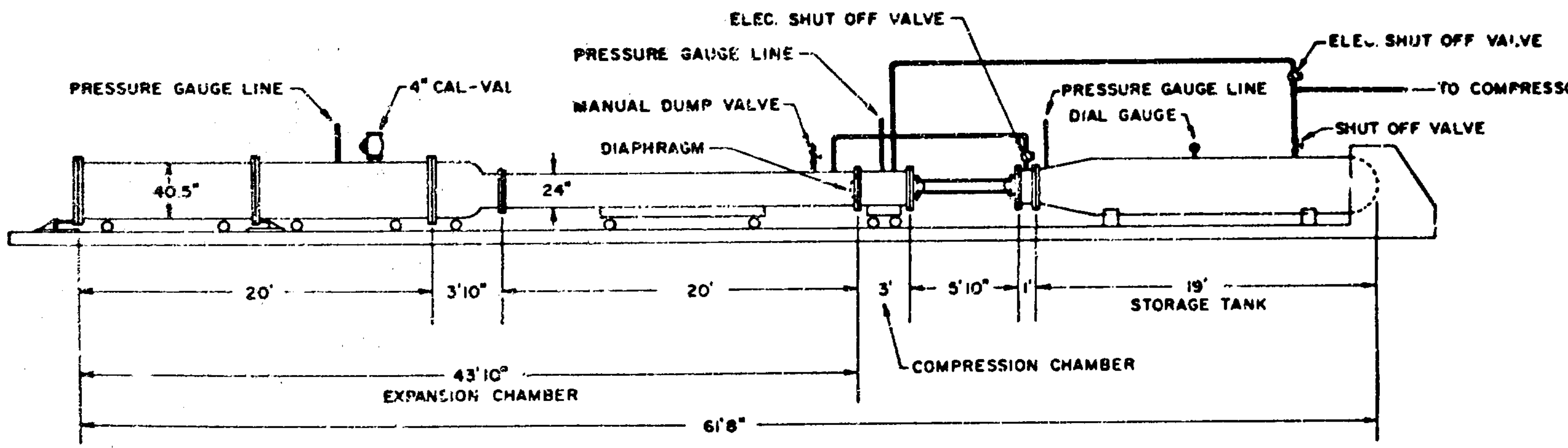


Figure 4. Detail Diagram 24-40-Inch Diameter Shock Tube (Variable Ambient Pressure Configuration).

Figure 5. 24-40-Inch Diameter Shock Tube (Variable Ambient Pressure Configuration).

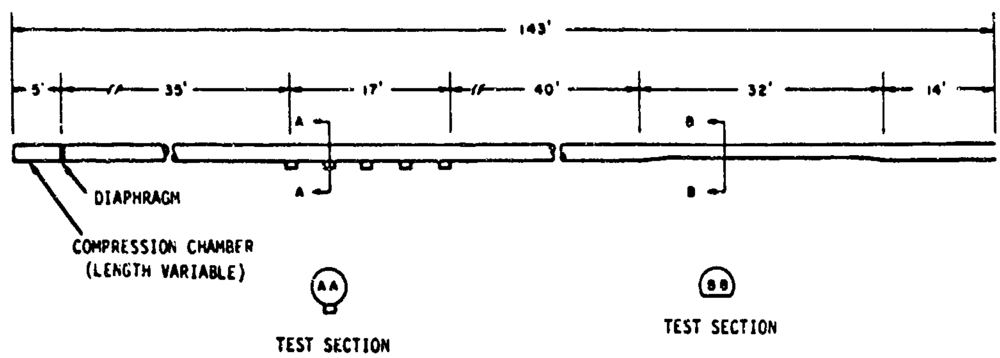


Figure 6. Detail Diagram 24-Inch Diameter Shock Tube.

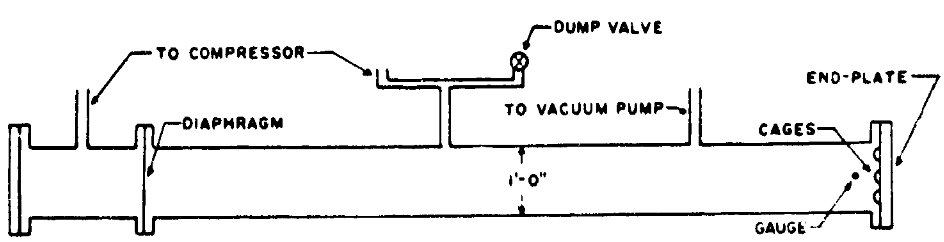


Figure 7. Detail Diagram 12-Inch Diameter Shock Tube.

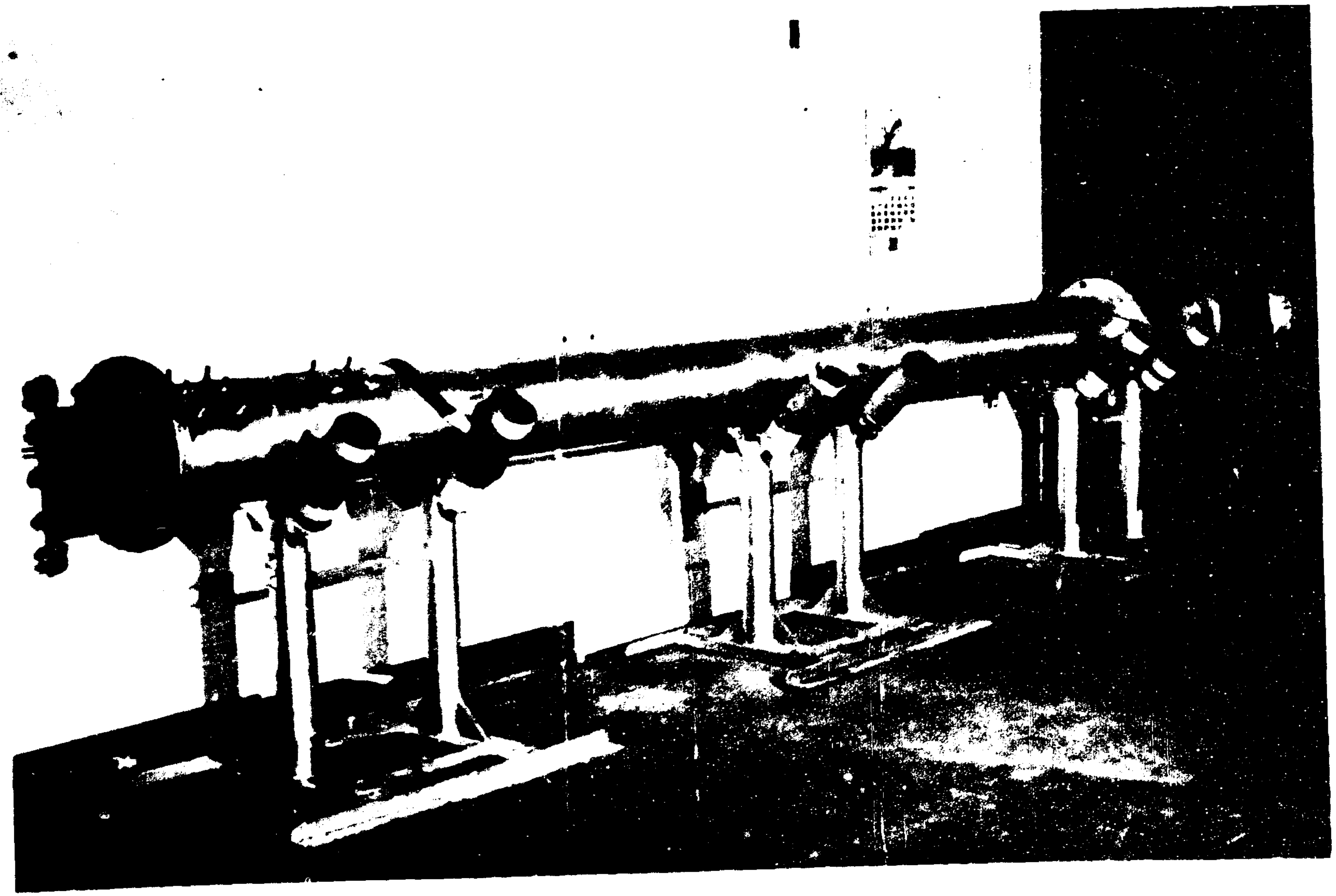


Figure 8. 12-Inch Diameter Shock Tube.

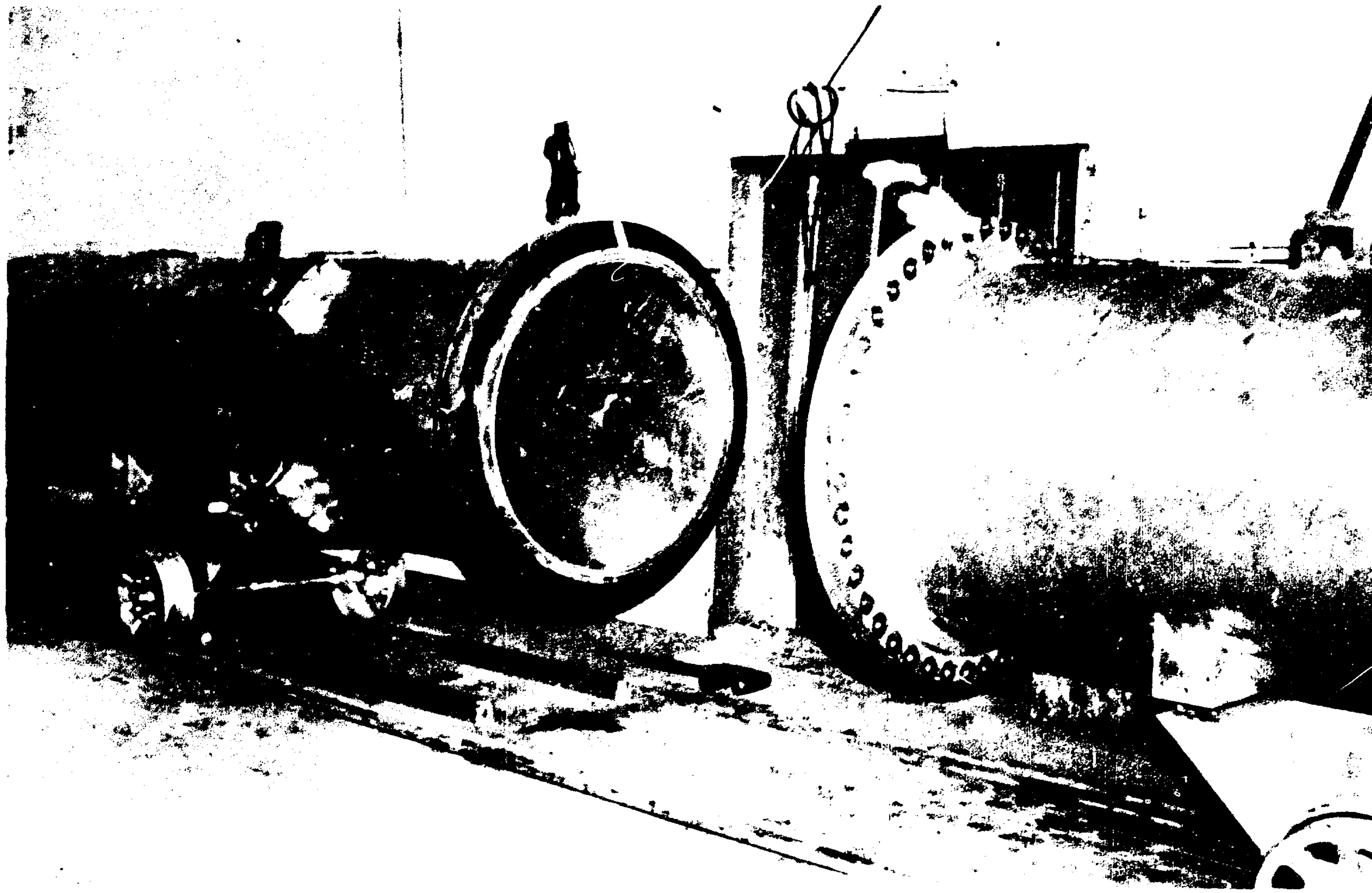


Figure 9. Diaphragm Station 42-72-Inch Diameter Shock Tube.

when operated under variable ambient pressures, are self-ruptured under pressure.

The thickness of the diaphragm determines the pressure held in the compression chamber. Curves showing pressure held versus diaphragm thickness for the different shock-tube diameters are given in Figure 10.

Concrete-Pad High-Explosive Test Site

This site (Figures 11 and 12) consists of a 60-ft diameter, 6-in. reinforced concrete pad with a concrete apron extending 80 ft to the west. Instrumentation housing includes a 7 x 12-ft diameter underground bunker located 84 ft from the center of the pad for pressure-time recording equipment, an aboveground firing- and camera-control bunker, and camera towers. Pressure-gauge mounts are located in the lids of steel boxes flush with the surface of the pad along several radii. Conduits, carrying gauge leads from these boxes to the recorders in the underground bunker, are embedded in concrete to provide shielding against spurious signals being introduced into the recording system. A similar system of conduits extends from the underground bunker to the area adjacent to the concrete pad where tests may be conducted on an earth pad and in full-scale foxholes and bunkers. Three poles have been installed around the circumference of the concrete pad to provide for variable height suspension of the charge directly over the pad. At this test site, bare explosive charges of from 0.5 oz to 64 lb have been fired — use of much larger charges is possible.

INSTRUMENTATION

Most of the techniques for measuring pressures, including gauge design and calibration methods, have been adopted from those developed at the Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland.

Pressure Gauges

In most cases, piezoelectric gauges are used to measure pressure-time in the test environment. Cylindrical-shaped, piezoelectric gauges having sensing elements of tourmaline (Susquehanna ST-5), quartz (Kistler), lead metaniobate (Susquehanna ST-2), and lead zirconate (Susquehanna ST-2) are mounted side-on in the shock-tube walls or in probes face-on to the flow to record total or stagnation pressures. These gauges have a frequency response from 40 to 250 kcs. More sophisticated gauges (Susquehanna ST-4), having a megacycle frequency-response, are mounted in surfaces normal with respect to the incident shock for monitoring reflected shock pressures. Pencil-shaped gauges measure side-on pressures above the surface and in the shock flow.

A typical instrumentation arrangement for the measurement of side-on pressures in a shock tube is shown in Figure 13. Using low-noise cables, Kistler charge amplifiers, and impedance-matching devices, the output from the recording gauge is measured and displayed on a cathode-ray oscilloscope. Permanent records are obtained by photographing the sweep with an attached Polaroid Land camera mounted in a periscope assembly. The oscilloscopes are normally set for a single sweep which is externally triggered by the signal from a gauge mounted a few inches upstream of the recording gauge. In order to ensure triggering the oscilloscope sweep, the signal from the triggering gauge

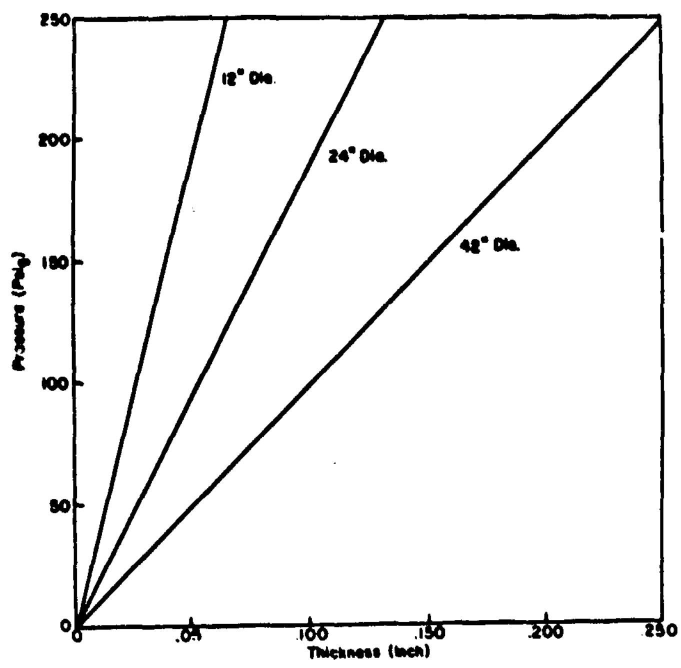


Figure 10. Diaphragm Thickness Versus Pressure-Held Curves.

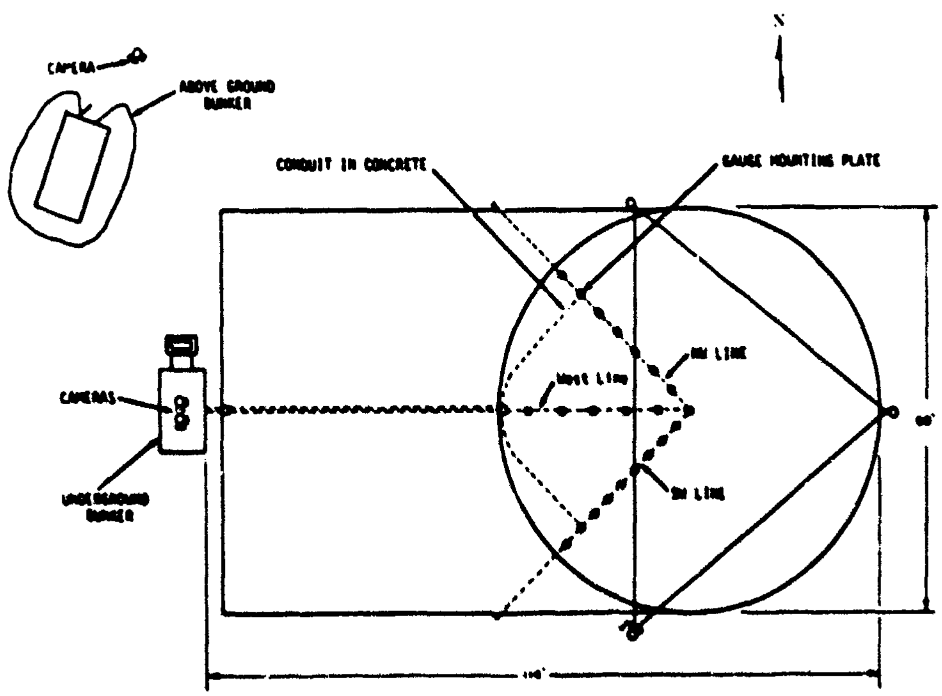


Figure 11. Diagram Concrete-Pad, High-Explosive Test Site.

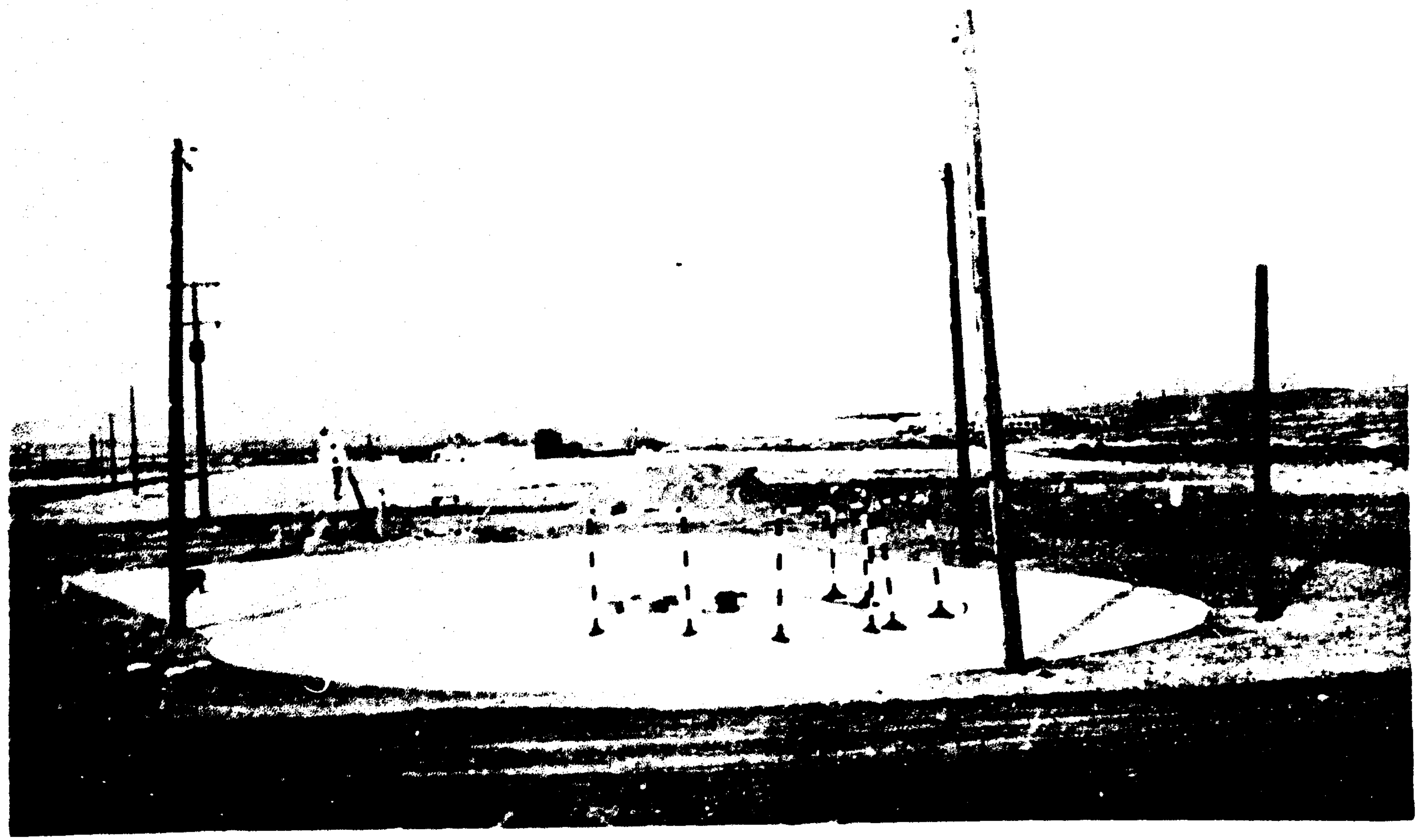


Figure 12. Concrete-Pad, High-Explosive Test Site.

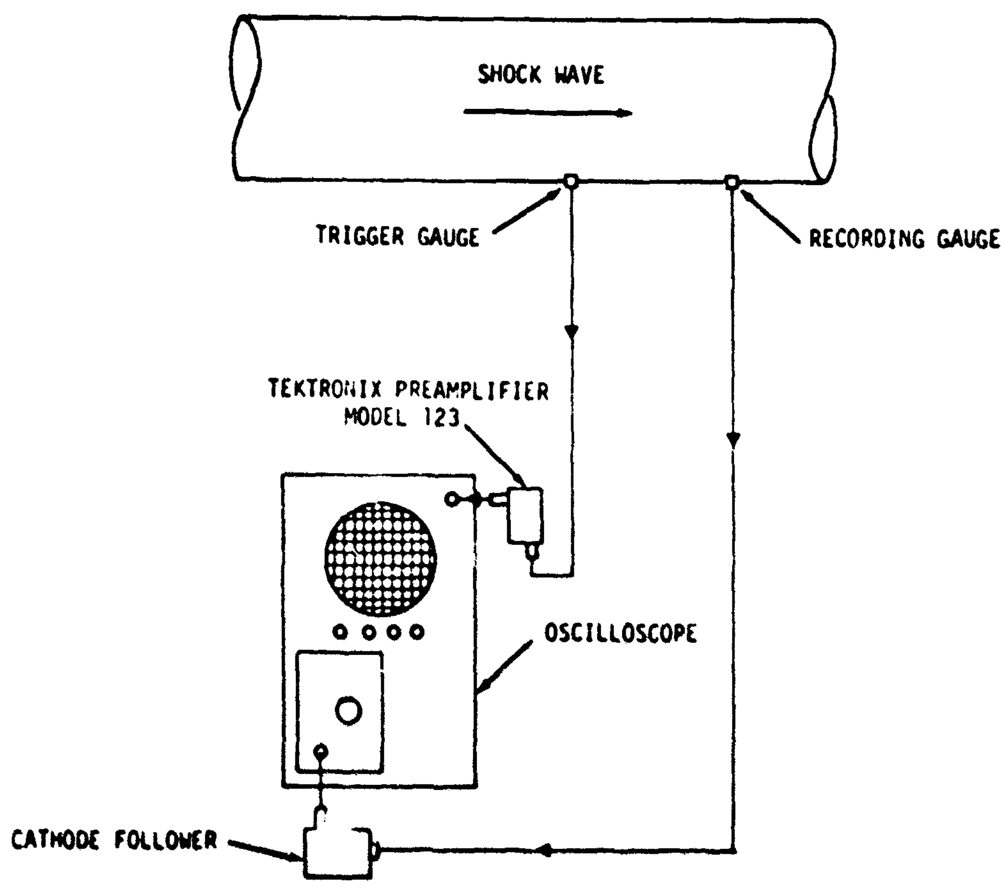


Figure 13. Instrumentation Diagram for Measuring Shock-Tube, Side-On, Hydrostatic Pressures.

is amplified by a Tektronix Preamplifier Model 123.

Piezoelectric gauges designed by the Atlantic Research Corporation for a fluid environment have been successfully used to obtain pressure-time patterns from inside anesthetized animals during blast-loading. These gauges record data vital to the development of mathematical models describing the response of the chest to pressure changes.[1] A small transducer (Model LC-5) measuring 0.09 in. in diameter and 0.75 in. in length has a frequency response of 500 kcs in water and 35 kcs in air. Its small size permits easy insertion into the esophagi and tracheae of rats and guinea pigs. Larger transducers (Models BC-10 and LC-10) measuring 0.38 in. in diameter and 1.13 in. in length are used for rabbits, dogs, and sheep.

A recent advance in instrumentation procedures at this facility now provides a continuous readout of piezoelectric-gauge signals passed through galvanometers into an oscillograph recorder. As illustrated in Figure 14, the output of the recording piezoelectric gauge, amplified by a Kistler Charge Amplifier Model 504, is fed into a Honeywell Galvanometer Amplifier Model T6GA and then into a Honeywell Visicorder Model 1508. Although this system has a low frequency response, it is acceptable for many of the experiments. A typical oscillograph readout from this arrangement, using the 12-72-in. diameter shock tube, is shown in Figure 15.

High-Explosive, Test-Site Instrumentation

A diagram of the instrumentation at the high-explosive test site, showing both high-speed camera and pressure-time coverage, is shown in Figure 16. A signal from the hand switch starts the cameras, and when the cameras reach the desired speed for the test, the delay-timer detonates the charge. At a preset time after the detonation, the camera-limit timer shuts down the cameras. A signal from a piezoelectric triggering gauge, mounted in a probe directly below the charge, is fed through a Tektronix Model 123 Preamplifier to ensure external triggering of the oscilloscopes at the proper time. Signals from the piezoelectric gauges are passed through 100-ft lengths of low-noise cables to cathode followers and on into the oscilloscopes where attached Polaroid cameras provide a permanent photographic record of the overpressures. There are 18 separate pressure-time recording channels available at the high-explosive test site.

Pressure-Gauge Calibration

A pressure gauge with its associated cables, cathode follower, and preamplifier are routinely calibrated as a unit. Normally, pressure gauges for shock tubes are calibrated with a pulse calibrator; however, other methods such as shock velocity, gauge-pairing, and comparison with shock-tube calibration curves are used. Pressure gauges, cables, and channels of the instrumentation system at the high-explosive test site are given a pre-test check by the explosive method using a 1-lb pentolite sphere. Recorded pressures, durations, and arrival times for each pressure gauge are compared with standard calibration curves.[2]

Experience has shown that a push-button gauge calibrator is ideal for applying known pressure pulses to gauges at either the shock tube or in the field. A diagram of such a calibrator, an earlier model of which has been described by Coulter,[3] is shown in Figure 17. A large tank of air, in which the pressure is accurately determined by a Heise dial gauge, is separated by a fast-opening valve from a chamber of small volume into which the gauge to be calibrated is

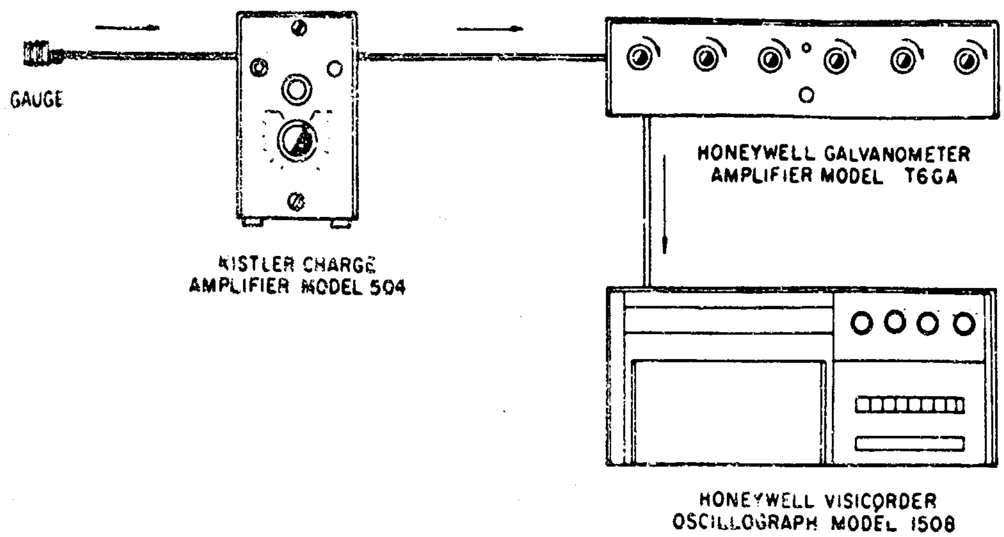


Figure 14. Instrumentation Diagram for Visual Readout Recording of Shock-Tube, Pressure-Time Waveforms.

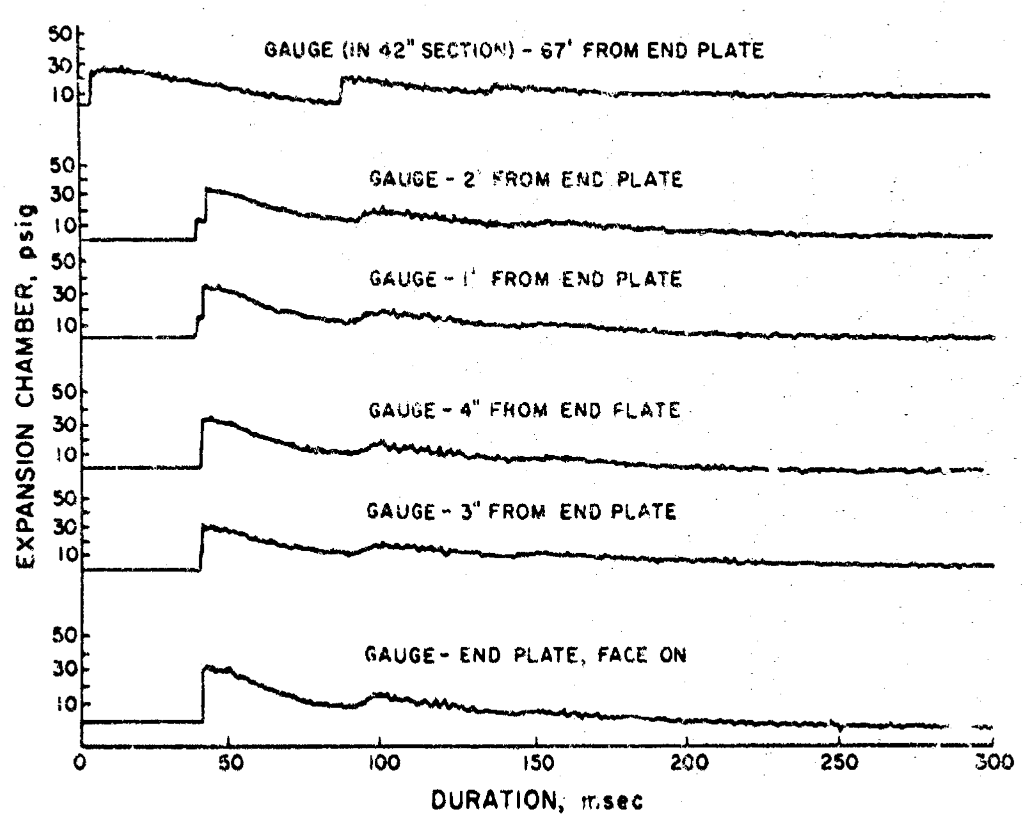


Figure 15. Visual Readout Recording of Pressure-Time Waveforms in 42-72-Inch Diameter Shock Tube.

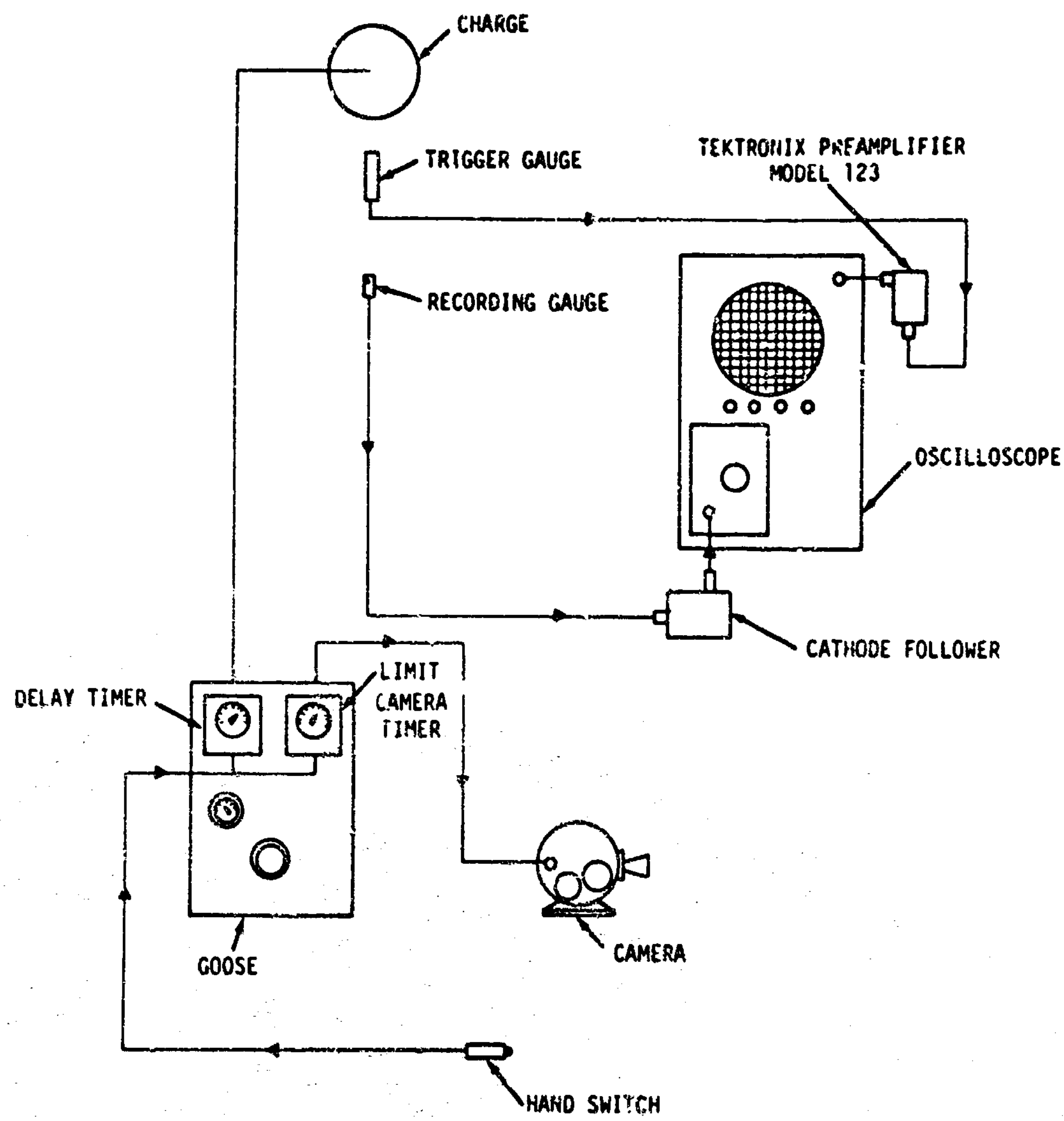


Figure 16. Instrumentation Diagram for High-Explosive Test Site.

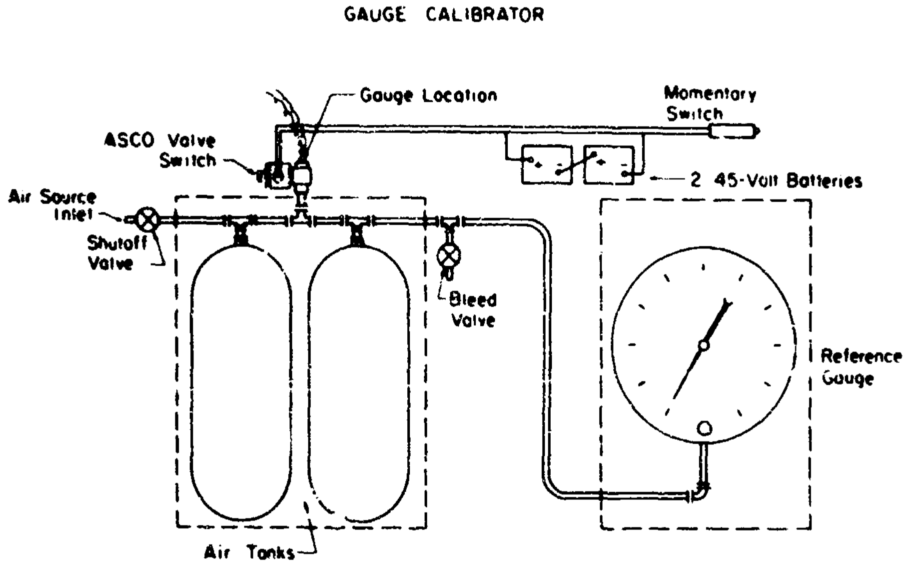


Figure 17. Diagram of Push-Button, Pressure-Gauge Calibrator.

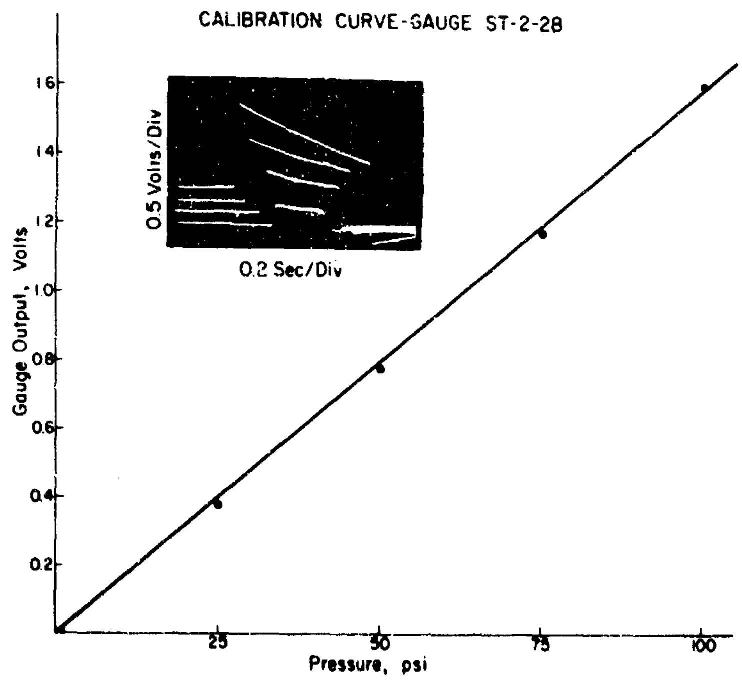


Figure 18. Typical Pressure-Gauge Calibration Curve.

fitted. Because the volume of the air at the output side of the valve is so small, the temperature and pressure of the gauge being calibrated are equal to that in the large reference tank when the fast-opening valve is actuated. The rise-time of the pressure on the gauge is approximately 12 msec. The voltage output of the gauge, as measured on an oscilloscope, is plotted versus pressure to obtain a calibration curve for that gauge. A typical calibration curve is shown in Figure 18. Adaptors are available for the pulse calibrator to accommodate transducers of other than cylindrical shapes.

Good agreement has been found between pressures measured by gauges calibrated by the pulse calibrator and other gauges, such as Kistler transducers that were calibrated statically because of their long time-constant and gauges that were calibrated from shock-velocity measurements.

PERFORMANCE CHARACTERISTICS

42-72-Inch Diameter Shock Tube

Calibration curves for the incident and reflected shocks of the 72-in. section and the incident shock of the 42-in. section have been prepared and are shown in Figure 19. The durations of the shock waves measured at the endplate of the 72-in. section, using driver pressures of 200-280 psi, were between 145 and 215 msec with a mean of 184 msec; in the 42-in. section, durations were in the order of 100 msec.

12-24-40-Inch Diameter Shock Tube

12-40-Inch Diameter Shock Tube

The initial configuration, conceived and assembled by J. Clark,[4] of the 12-40-in. shock tube is shown in Figure 20. It was designed primarily to duplicate, within a large chamber (40.5 in. x 7 ft), long-duration, pressure-time patterns as recorded inside personnel shelters containing animals subjected to nuclear blasts at the Nevada Test Site.[5,6] It was intended to reproduce these waveforms for biological hazard assessment to supplement full-scale testing. The compression chamber consisted of a 100-gallon butane storage tank (13.5 cu ft) with one end modified by the addition of a transition section that reduced the diameter from 3.45 to 2 ft over a 3-ft span or to 1 ft over an additional 2.3-ft span. The test section on the expansion side consisted of a [illegible] storage tank 40.5 in. in diameter and 7 ft long (40 cu ft) with appropriate flanges. As noted in Figure 20, a removable transition section permitted either 12- or 24-in. diameter diaphragms to be used. Various lengths of tubing or steel plates containing the metering orifices could be added at the locations indicated; thus, the rate of pressure rise, the peak pressure, and the rate of decay could be regulated within limits by varying configuration of the expansion chamber. Smooth-rising, pressure-time patterns that rose to 100 to 200 psi in 10 to 155 msec with durations of 5 to 20 sec have been tested with biological specimens.[7,8] An example of a smooth-rising pressure is given in Figure 21. With a given configuration, the wave shape did not vary over a wide range of driver pressures.

24-40-Inch Diameter Variable Duration Assemblies

To meet the objectives of determining the relationship of pulse duration to lethality from "sharp"-rising overpressures for animals, it was necessary

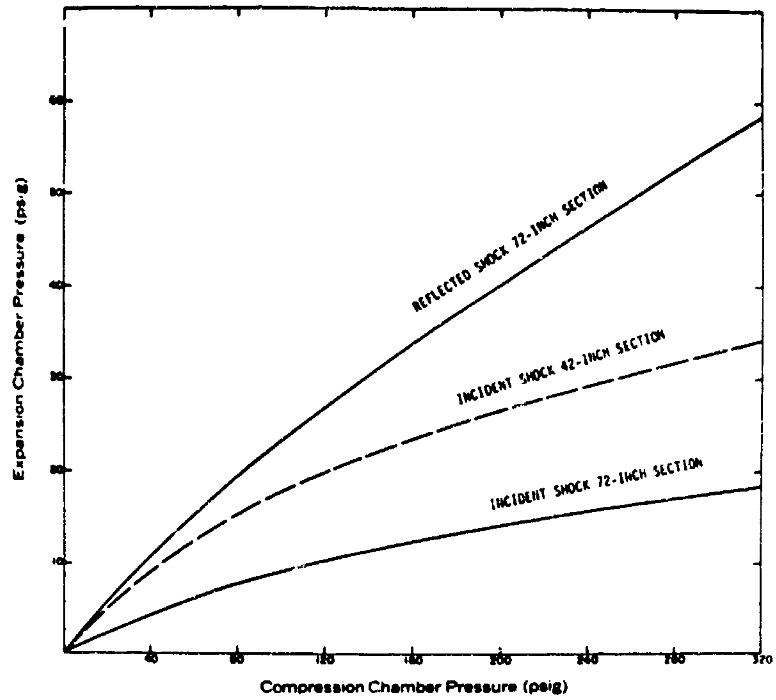


Figure 19. Calibration Curve for 42-72-Inch Diameter Shock Tube.

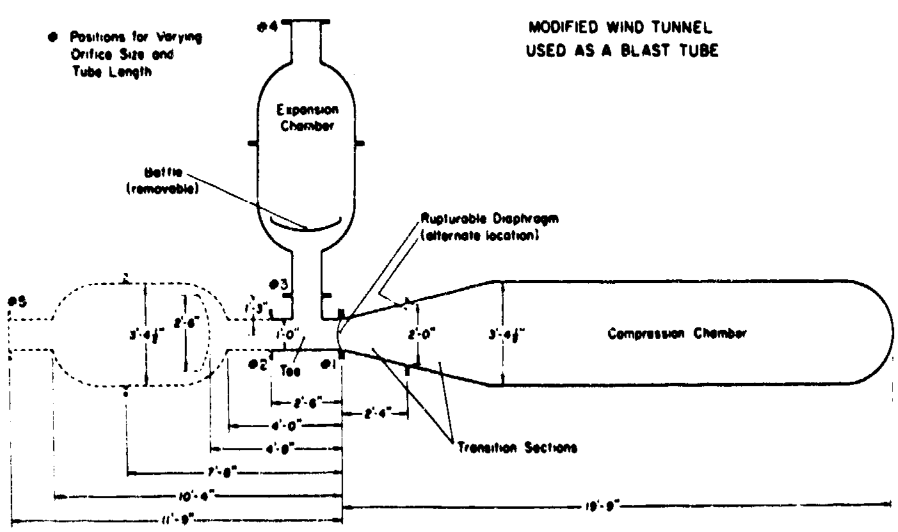
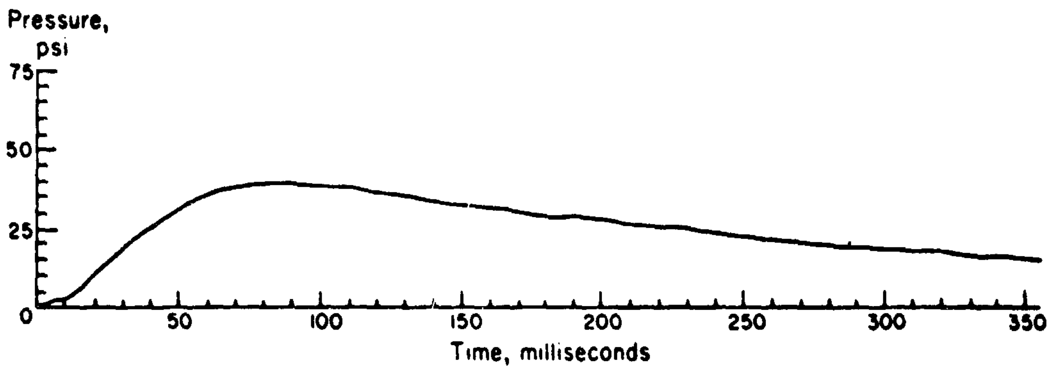


Figure 20. Initial Configuration for 24-40-Inch Diameter Shock Tube.



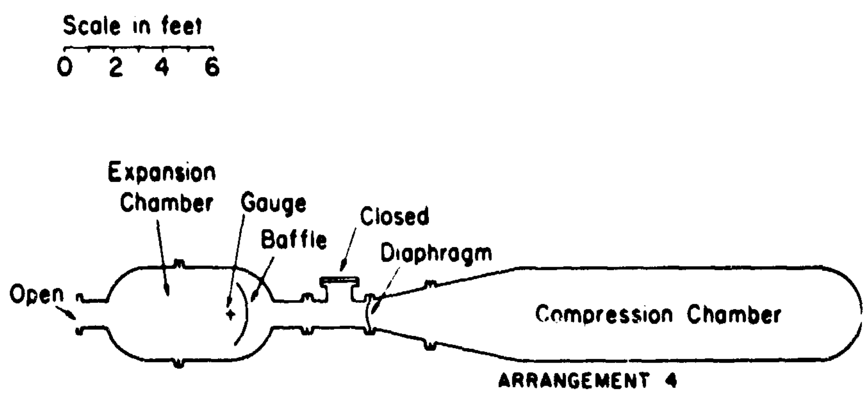


Figure 21. Smooth-Rising Pressure Curve from the 24-40-Inch Diameter Shock Tube (Arrangement 4).

to produce pressure pulses of progressively shorter durations. Figures 22 and 23 illustrate the sequence of modifications to the 24-40-in. diameter shock tubes that served to accomplish this. Also shown are the associated pressure-time curves.

Starting with shock-tube configuration A" (Figure 22), which gave a 400-msec wave, the pulse was shortened to 75 msec (Figure 22-I), and to 54 msec (Figure 22-I_2) by replacing the 17-ft x 40-in. driver with 10- and 5-ft lengths of 24-in. tubing, respectively. At the same time, the 24-in. diameter portion of the expansion section was reduced from 30 to 20 ft and a fourth vent added.

By further decreasing the lengths of the driver and driven components and introducing gaps between some of the flanges on the expansion side, durations of 34, 21, and 15 msec were obtained (Figures 23-J, -K, and -L). The use of gaps as shown in Figures 24 and 25 was a simple means of obtaining additional rarefaction waves to reduce the duration.

24-40-Inch Diameter Variable Ambient Pressure Modification

The recent configuration modification of the 24-40-in. diameter shock tube provides for evacuation or pressurization of the expansion chamber to simulate increased or decreased ambient pressures. (See Figure 4.) Initial calibration curves, subject to further testing and improvement, are being prepared for ambient pressures of 0.5, 1.0 and 1.5 atmospheres.

Performance characteristics are generally similar to those noted later for the 12-in. shock tube. (See Figure 29.)

24-Inch Diameter Shock Tube

Movable Endplate Assembly

The techniques involving the 24-in. diameter shock tube for exposing animals to pressures that rise in one or two steps (shocks), with the time between shocks varied, are shown in Figure 26.[9] The animals were placed in recesses one-body diameter deep in the wall of the tube. A reflecting plate mounted on threaded rods was placed at the animals' lungs or at short distances downstream. With the reflecting plate directly over the animals' thoraces, their lungs (target organs) were subjected to incident and reflected shocks almost simultaneously (Figure 26-C-I). With the reflecting plate at 1, 2, and 3 in. downstream from the thoraces, the lungs were exposed to incident and reflected shocks separated by time-intervals of 0.14, 0.28, and 0.42 msec, respectively (Figures 26-C-I_1, -C-I_2, and -C-I_3). These small time-intervals are important to the response of the animals to overpressure; it is analogous to a man being exposed to an air blast at short distances from a reflecting surface normal to the incident shock and in foxhole or bunker geometries. This tube is operated with the end closed for these tests.

Model Foxhole Assembly

In the past, the 24-in. diameter shock tube has been utilized for model foxhole studies.[10] The studies were aimed at establishing the tolerance of animals in terms of "free-field" overpressures and in various geometries of exposure. An incident pulse, comparable to an overpressure that might occur "free field" in the absence of buildings and over a fairly level terrain, was generated using the 24-in.

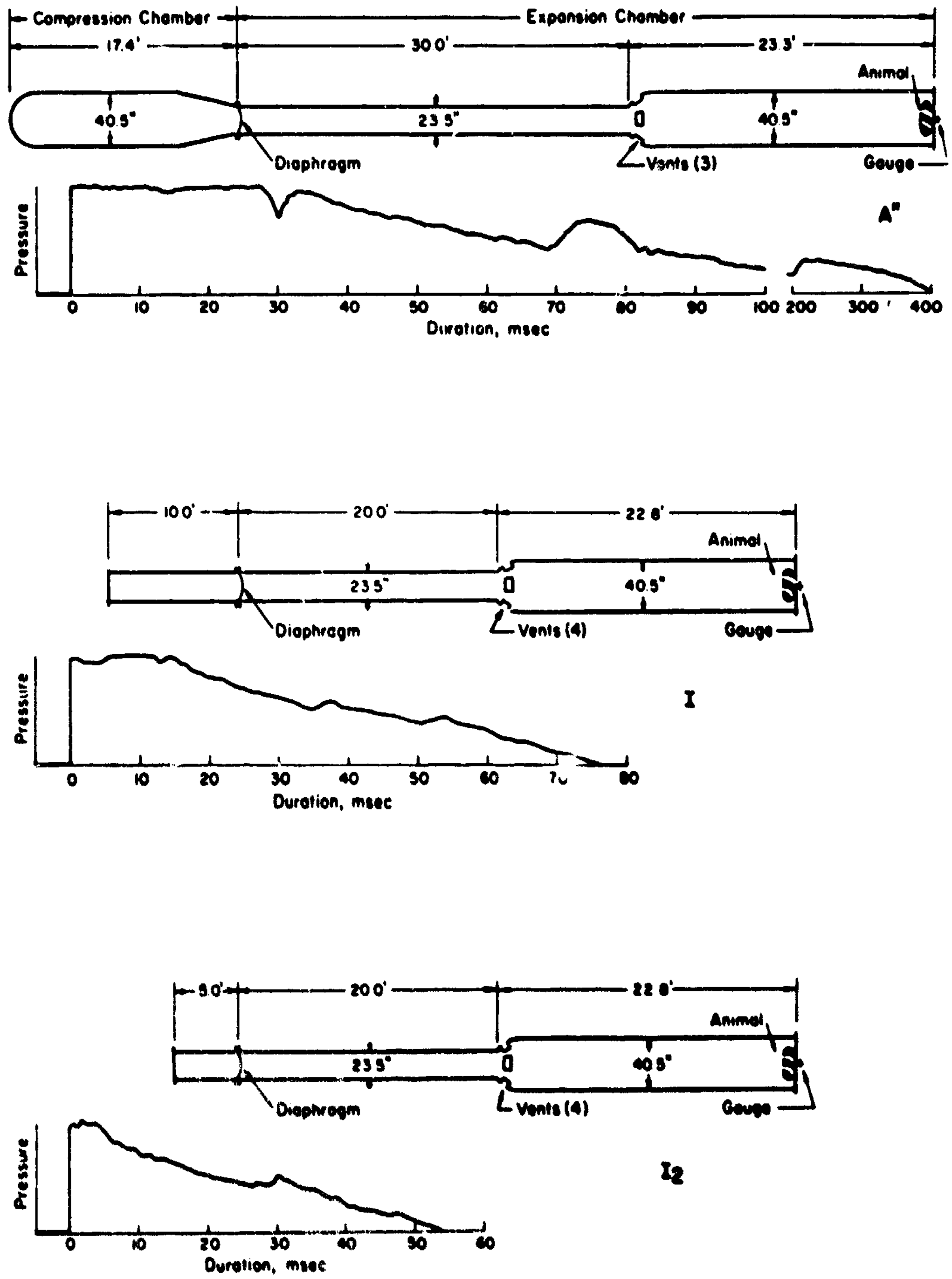


Figure 22. Modification Diagrams and Associated Pressure-Time Recordings for 24-40-Inch Diameter Shock Tube (Sequence 1).

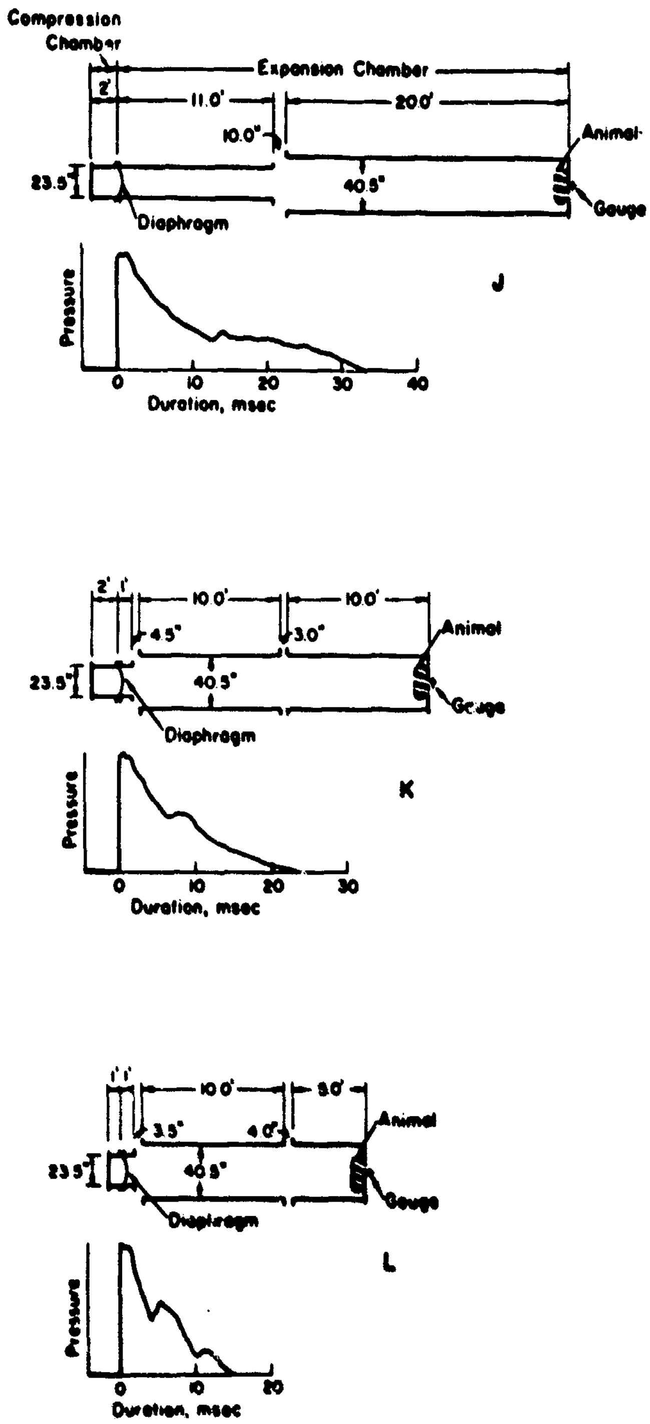


Figure 23. Modification Diagrams and Associated Pressure-Time Recordings for 24-40-Inch Diameter Shock Tube (Sequence 2).

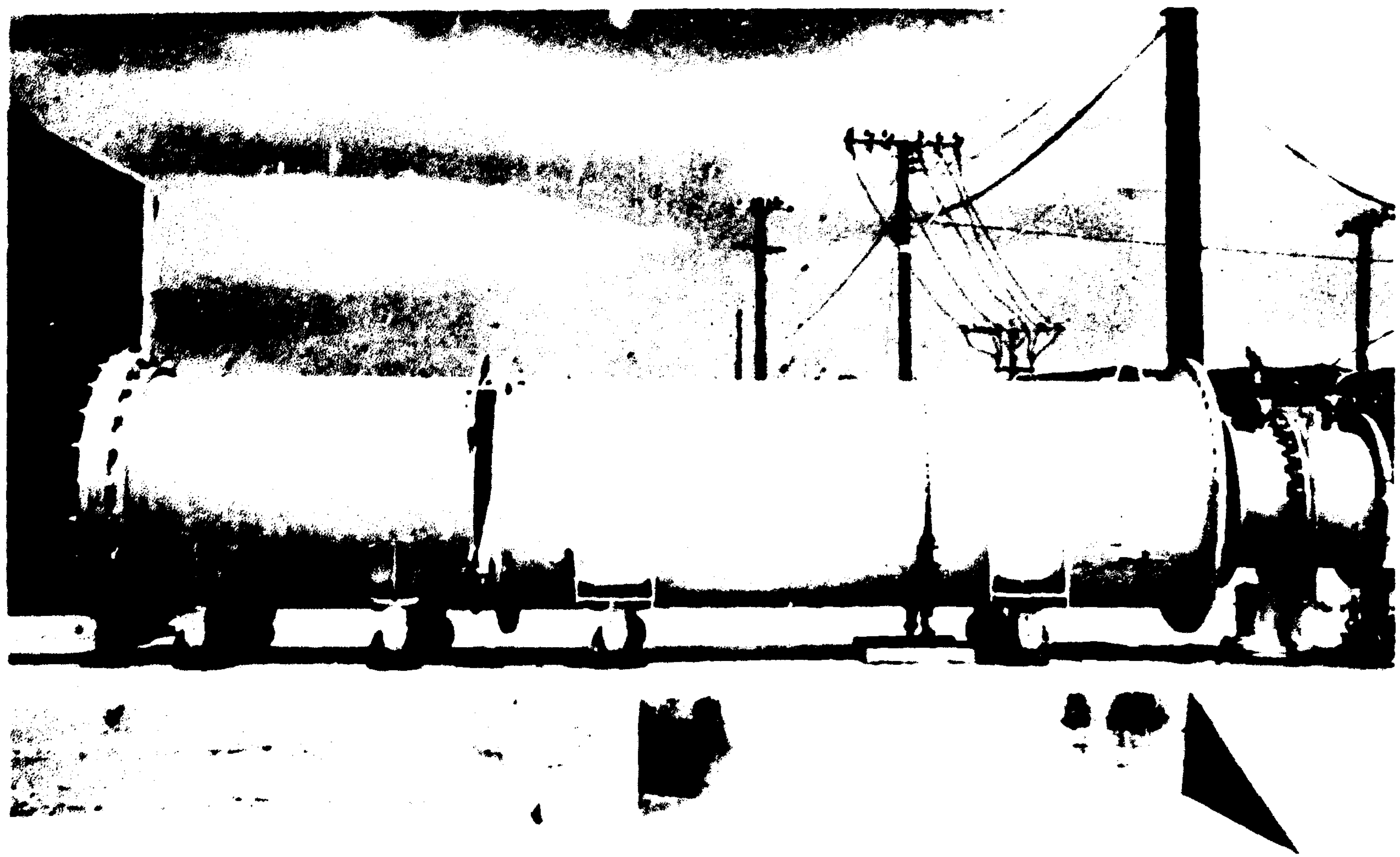


Figure 24. Gap Configuration in 24-40-Inch Diameter Shock Tube (Arrangement L).

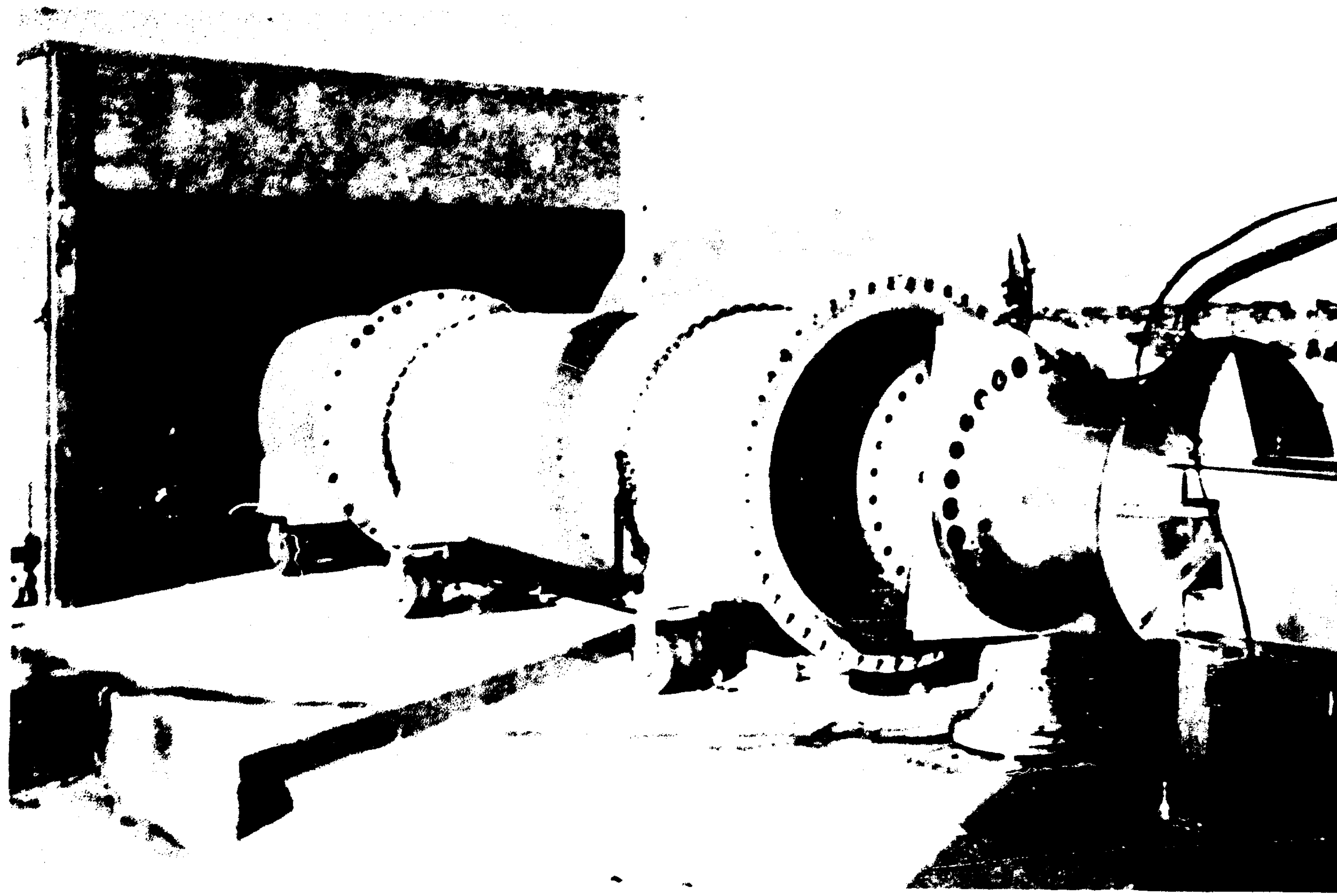


Figure 25. Gap Configuration in 24-40-Inch Diameter Shock Tube (Arrangement K).

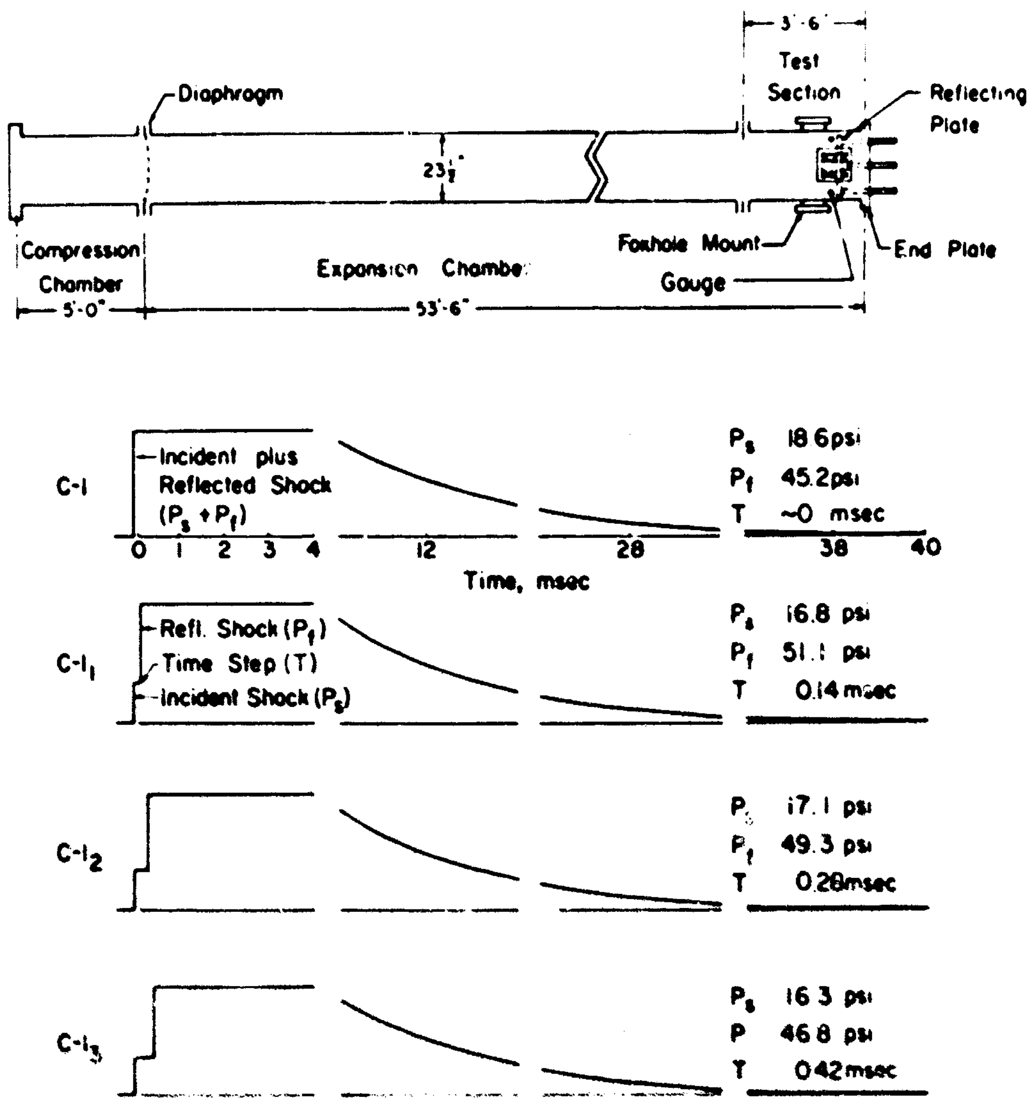


Figure 26. Shock-Tube Configuration and Two-Step, Pressure-Time Recordings for 24-Inch Diameter Shock Tube.

diameter shock tube employed open-ended. The pulse variations were also measured inside rectangular chambers of various designs in which guinea pigs were placed. Typical recordings are shown in Figure 27. The variations in waveform at various locations are of considerable interest from both the physical and biological points of view.

Calibration Curve

A calibration curve for incident shocks in the 24-in. diameter shock tube is shown in Figure 28. Durations recorded during calibration varied from 36 to 60 msec for shocks ranging from 17 to 33 psi.

12-Inch Diameter Shock Tube

Small animal species were subjected to air blast while at different ambient pressures in the 12-in. diameter shock tube.[11] The shock-tube configuration and the pressure-time profiles representative of reduced and increased ambient pressure environments are shown in Figure 29. In these tests, it was necessary to return the pressure to pre-shot level as quickly as possible and to hold it there for one hour, which was the endpoint of the experiment. This tube is also used for the dynamic calibration of transducers and in the development of gauge mounts. A calibration curve for the 12-in. diameter shock tube, used open-ended, is shown in Figure 30.

FUTURE PLANS

Future modification plans for the 42-72-in. diameter shock tube include the installation of a hydraulic closing system for the diaphragm station, a driver using gas or solid explosive, and an extension of the 72-in. section for free-stream, open-ended testing.

Installation of a Schlieren system and a square test section with high-quality glass ports is under way on the 24-in. diameter shock tube. When completed, this system will be used to study the blast-wave diffraction patterns around small animals in free-stream and other geometries of exposure.

A system to take microsecond X rays of animals while being exposed to air blasts is under development for the 12-in diameter shock tube. It is planned to use a time-sequencing method for successive shots in order to provide for step photos of organ displacement with reference to the mechanism of injury that follows exposure to blast-induced variations in pressure.

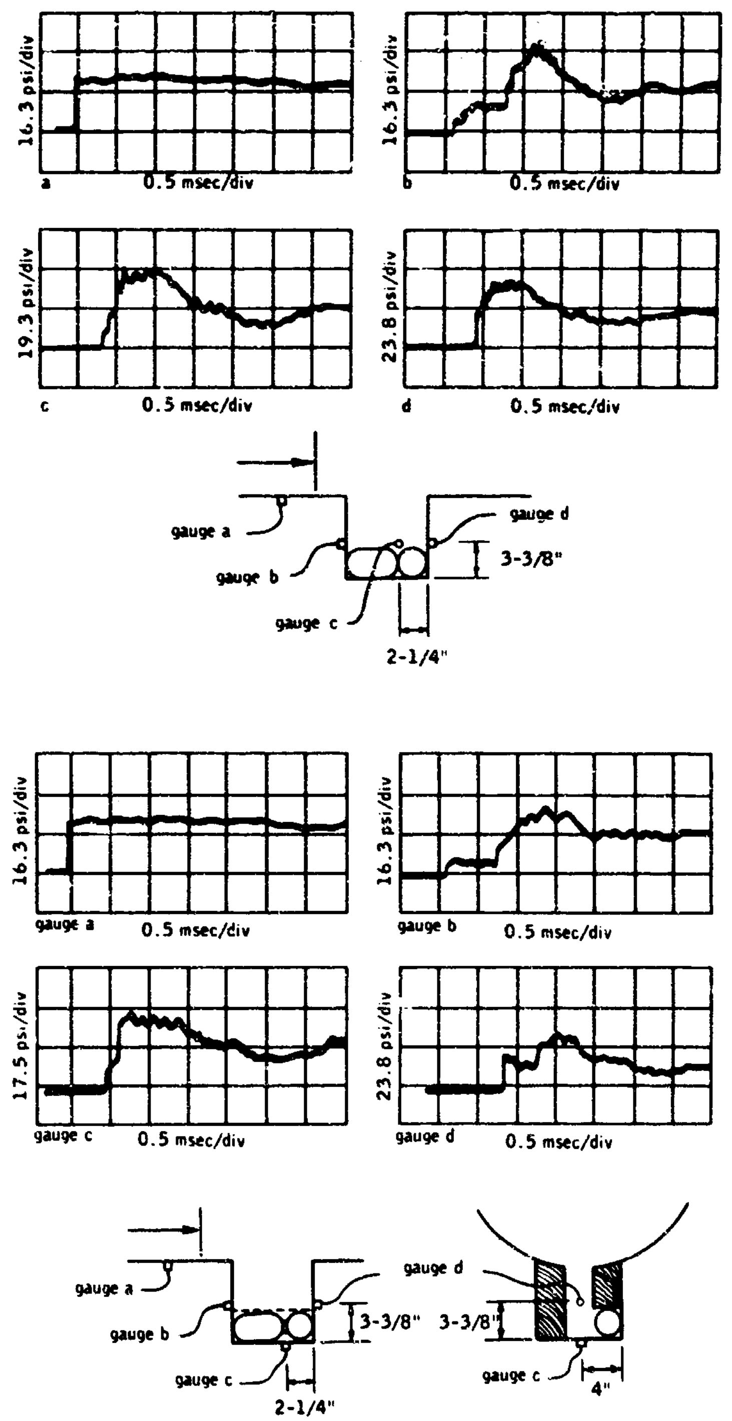


Figure 27. Typical Pressure-Time Curves Recorded Free-Stream and Inside Rectangular Chambers.

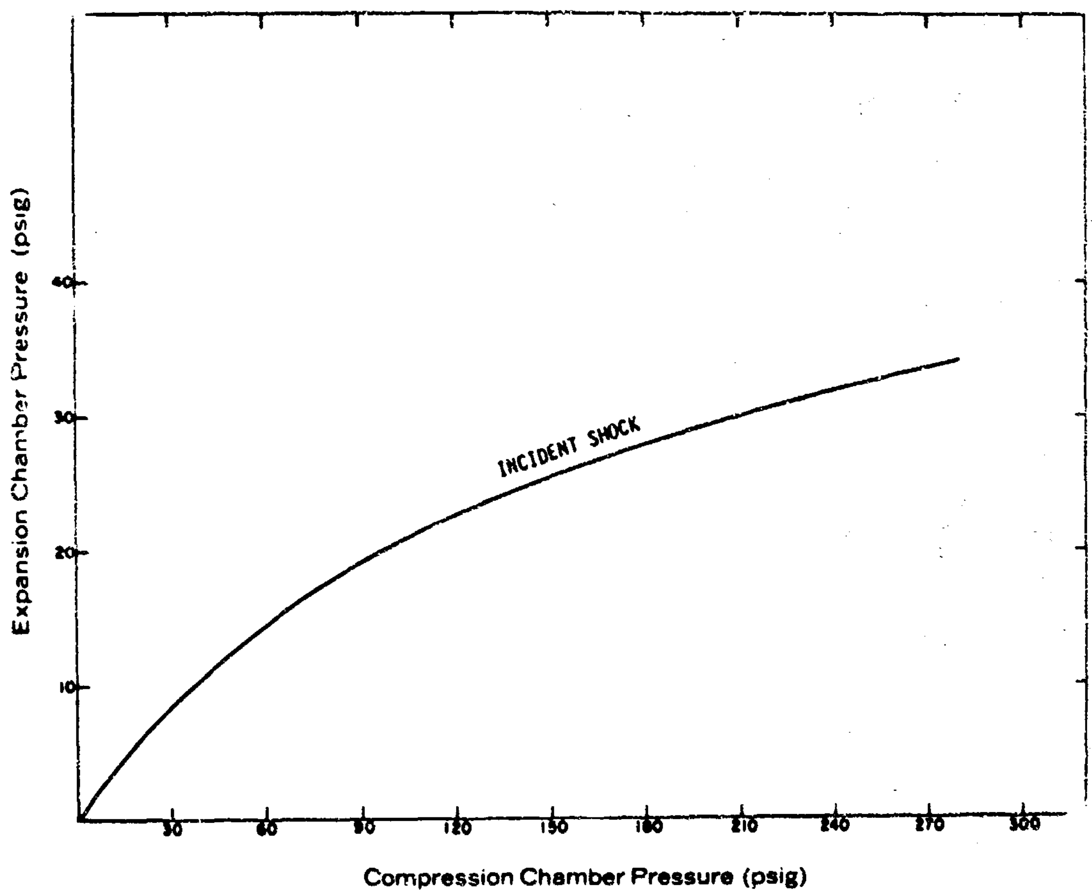


Figure 28. Calibration Curve for 24-Inch Diameter Shock Tube.

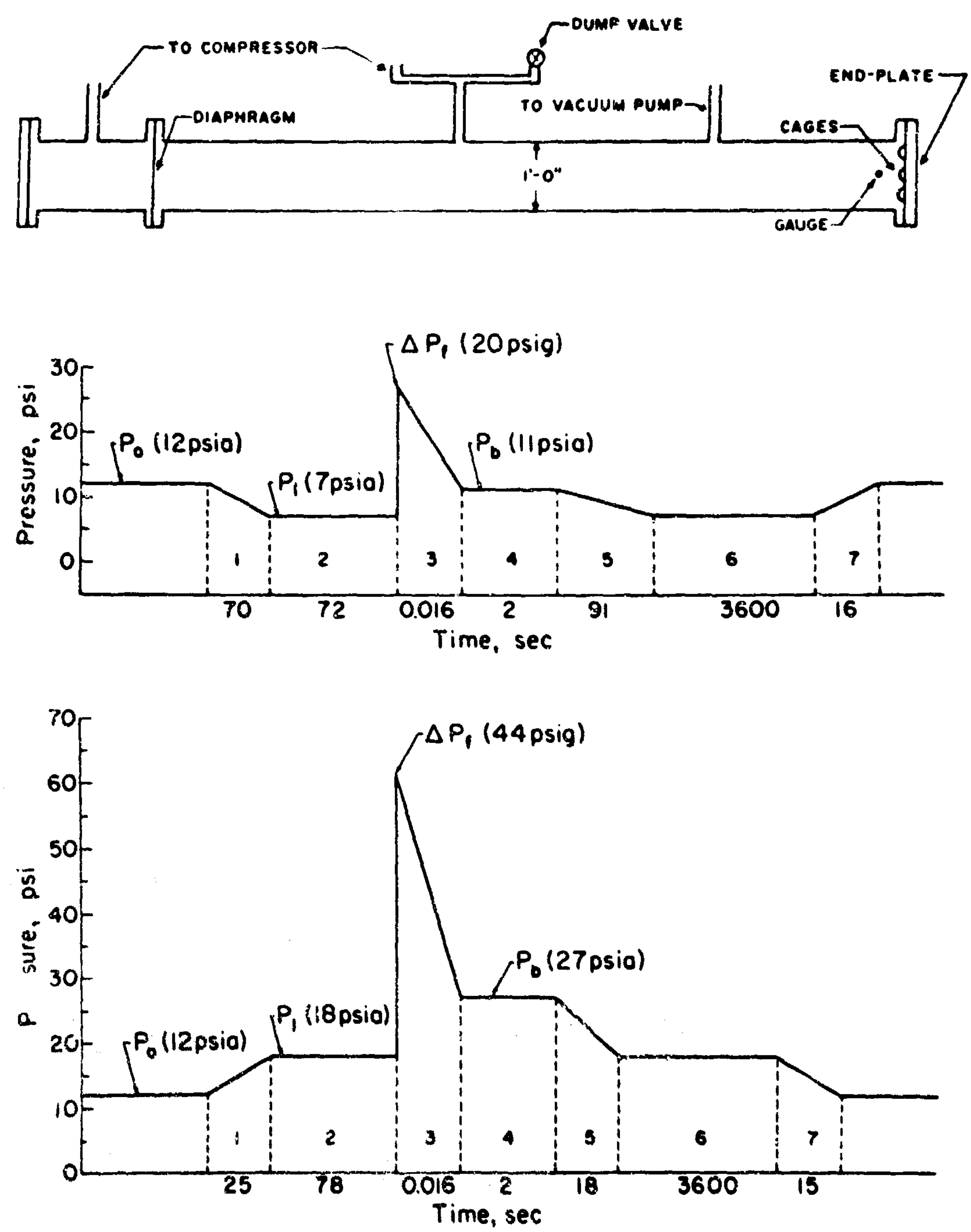


Figure 29. Shock-Tube Configuration and Pressure-Time Profiles for Reduced and Increased Ambient Pressure Environments in the 12-Inch Diameter Shock Tube.

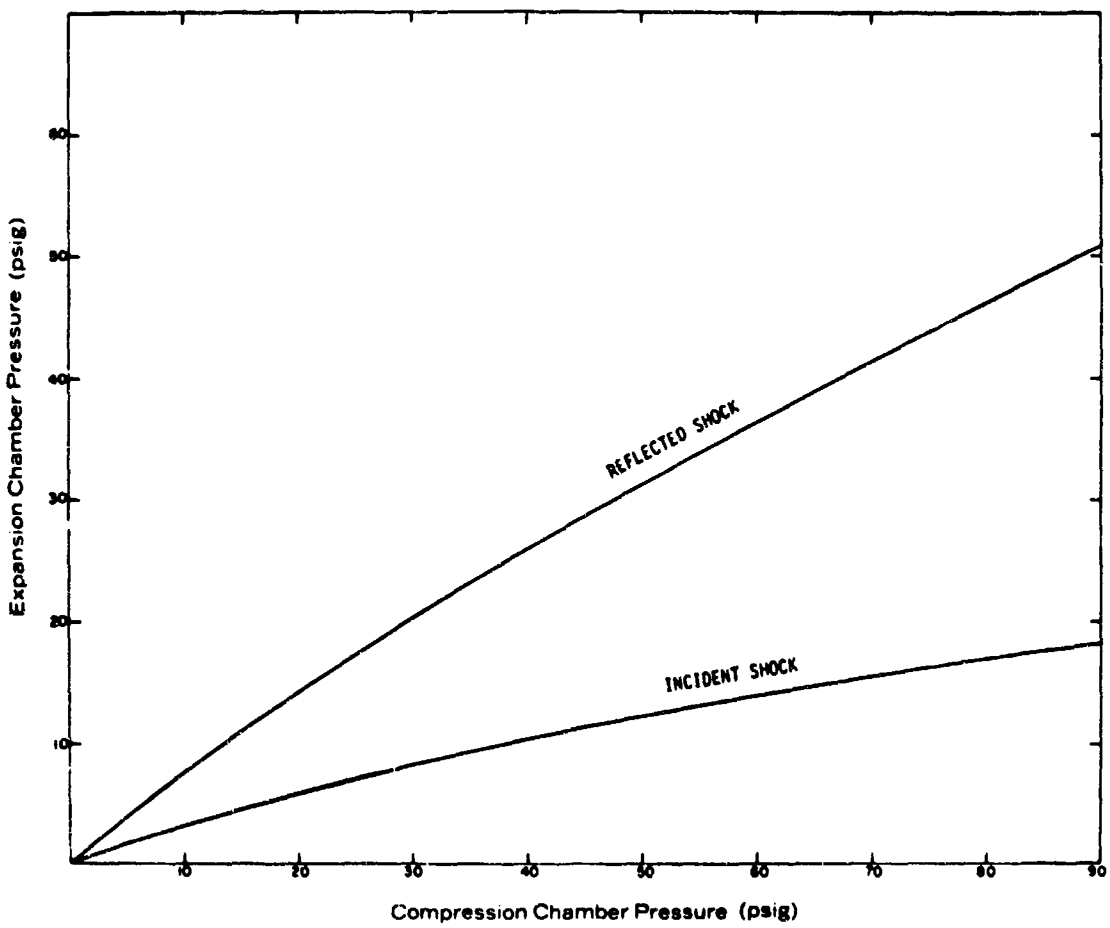


Figure 30. Calibration Curve for 12-Inch Diameter Shock Tube.

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13. ABSTRACT

The DASA-AEC-Lovelace Foundation Blast-Simulation Facility for the biomedical investigation of the effects of blast and shock is described in detail.

Photographs, descriptions, and specifications of four air-driven shock tubes, ranging from 12 to 72 inches in diameter, and a concrete-pad, high-explosive test site are given. The instrumentation system and shock-tube and gauge-calibration procedures are included.

Test parameters for each shock tube are briefly summarized and supported by typical pressure-time patterns and calibration curves.

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14 KEY WORDS	LINK A		LINK B		LINK C	
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